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Analysis of Transmission Methods for Ultra-Reliable Communications

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Abstract—Fifth generation of cellular systems is expected to widely enable machine-type communications (MTC). The envisioned applications and services for MTC have diverse requirements which are not fully supported with current wireless systems. Ultra-reliable communications (URC) with low-latency is an essential feature for mission-critical applications, such as industrial automation, public safety, and vehicular safety applications. This feature guarantees a communication service with a high level of reliability. This paper investigates the feasibility and efficiency of URC over wireless links. It also analyzes the effectiveness of different transmission methods, including spatial diversity and support of hybrid automatic repeat request (HARQ). Finally, the importance of reliable feedback information is highlighted.

Index Terms—5G, machine-type communications, machine-to-machine communications, ultra-reliable communications, low-latency, diversity, HARQ, channel feedback

I. INTRODUCTION

Fifth generation (5G) of cellular networks is considered as a converging technology to provide connectivity for a wide range of devices and applications. It will not only increase the offered data rates, but also embrace new features [1]. The new features are mainly essential to support machine-type communications (MTC) or machine-to-machine (M2M) communications. The communication and connectivity requirements for MTC are very diverse. One of the considered features for MTC is the support of ultra-reliable communications (URC) with low-latency. This entails to guarantee a certain level of communication service with high level of reliability [2]. The URC is vital for the safe operation of many applications, in particular, industrial automation, public safety, and vehicular safety applications.

URC is generally associated with low-latency transmissions. This indicates that a message should be delivered with high reliability within a short time. For mission-critical applications, an extreme level of certainty is also essential. Meeting these requirements in wireless systems requires modifications in physical channel structure, channel coding, medium access control, and connectivity links [3].

Initial studies have considered different scenarios for 5G network [4]. For URC operation, it is proposed to provide certain communication rates with reliability greater than 99% and end-to-end delay less than 1 ms [5]. In order to meet these stringent requirements, various network optimization and modifications have been highlighted. Some of these consid-

erations include: use of shorter transmission time interval (TTI), support of device-to-device (D2D) communications, deployment of ultra-dense cell, and implementation of massive multiple-input multiple-output (MIMO) antennas. The use of shorter TTI allows reducing the over-the-air latency for data transmissions. Another scheme to reduce the overall latency is the support of D2D communications which enables to form direct links between nearby devices without passing their data to the network [6]. The ultra-dense deployment of cells improves the link robustness in the network [7]. The implementation of massive MIMO antennas is another solution to improve the communication link quality by benefiting from spatial diversity.

Although the realization of URC is an important issue for 5G network, there are not many studies on its feasibility and practicality. The feasibility of URC operation depends on the reliability and latency constraints, determined by the application requirements, as well as the link quality. Several solutions are offered for adapting running applications to the URC operation. Availability indication is considered as an indicator for applications to assess the availability of URC operation over the link [8]. In order to offer URC in various conditions, reliable service compositions are considered to offer different versions of URC for users [2]. A User can choose the proper service among the offered services according to its channel condition.

This paper investigates the feasibility of URC in wireless systems. It analyzes the channel condition in which a given level of reliability becomes achievable. It presents the trade-off between radio resource utilization and the level of reliability for applications that require decoding of short-length messages. In addition, it analyzes the effectiveness of various transmissions methods, such as spatial diversity and hybrid automatic repeat request (HARQ), in improving the link quality and the radio resource utilization. Finally, the paper highlights the effects of feedback channel error on the performance of URC.

The rest of the paper is organized as follows. Section II describes the system assumptions which are considered in the paper. Section III analyzes the feasibility and the resource utilization for URC using various transmission schemes. The effects of errors in a feedback channel are explained and assessed in Section IV. Finally, conclusions are drawn in Section V.

II. SYSTEM ASSUMPTIONS

We consider a link between two devices in a general cellular system. This link can be between a base station and a mobile device, or between two mobile devices in a D2D communication scenario. URC is considered for delivering short-length messages originating from the source device to the destination. Short amount of data is a common characteristic of many applications requiring ultra-reliability for their operation. Data transmissions are performed by employing channel coding and fitting the encoded data into symbols for over-the-air data transmissions. Since in wireless communications the link condition changes over time, the transmitter needs to perform link adaptation accordingly for achieving the reliable data transmissions. We assume that the link adaptation is performed by an adaptive channel coding scheme utilizing code words with different lengths. The average of signal energy for code words remains the same which means the signal-to-noise ratio (SNR) at the receiver does not depend on the length of transmitted code words. Furthermore, a Quasi-static channel is considered as the lengths of messages and code words are short [9]. So, the channel gain is the same for the symbols within a code word, while it changes for different code words. In order to perform the link adaptation, the transmitter requires to obtain channel side information (CSI) to adapt its transmissions. Hence, a feedback channel is utilized to carry CSI to the transmitter. This channel can also carry feedback error control information in case of using HARQ scheme.

III. TRANSMISSION METHODS FOR ULTRA-RELIABLE COMMUNICATIONS

This section investigates the feasibility of URC for a certain level of reliability over a wireless link. In addition, it analyzes the required radio resources for achieving this goal. The theoretical analysis, given in this section, illustrate the fundamental barriers for the realization of URC arise from the changes in the link condition.

We study and analyze three scenarios as follows:

- *A*: Single-input single-output (SISO) antenna system with no retransmission,
- *B*: Spatial diversity with no retransmission,
- *C*: Spatial diversity with HARQ.

A. SISO system with no re-transmission

We start by investigating the minimum required resources to achieve a certain level of reliability over an additive white Gaussian noise (AWGN) channel. In order to meet the reliability constraint for short-length data transmissions, a channel coding with finite block length can be considered. It was shown that over AWGN channel with SNR of γ at the receiver, the following relation is hold [10]:

$$\log_2 M(n, \epsilon, \gamma) = nC_1(\gamma) - \sqrt{nV_1(\gamma)}Q^{-1}(\epsilon) + \rho_n, \quad (1)$$

where $Q^{-1}(\cdot)$ denotes the inverse of the Gaussian Q -function. C_1 , V_1 and ρ_n are Shannon capacity, channel dispersion, and

error bound, respectively:

$$C_1(\gamma) = \frac{1}{2} \log(1 + \gamma), \quad (2)$$

$$V_1(\gamma) = \frac{\gamma}{2} \frac{\gamma + 2}{(\gamma + 1)^2} \log^2 e, \quad (3)$$

$$\rho_n = \mathcal{O}(\log n). \quad (4)$$

The approximation (1) indicates the maximum number of data bits which can be conveyed using n symbols and decoded with a block error rate (BLER) not greater than ϵ . For simplicity, we represent the maximum number of data bits by k . We also reform the approximation and express it as $E(n, k, \gamma)$ and $N(k, \epsilon, \gamma)$. The former function gives the maximum block error probability of decoding k bits of information using n symbols. The latter function determines the minimum required symbols to convey k bits of information with the considered BLER target.

$$E_{AWGN}(n, k, \gamma) = Q\left(\frac{nC_1(\gamma) - k}{\sqrt{nV_1(\gamma)}}\right), \quad (5)$$

$$N_{AWGN}(k, \epsilon, \gamma) = \min n : E(n, k, \gamma) \leq \epsilon. \quad (6)$$

Now, we can focus on the URC over a wireless link. A certain level of reliability cannot be achieved by considering that level for the reliability of all data transmissions. Accepting the radio resource limitation, the reliable data transmission is unfeasible when the channel gain is very low. Also in practice, a radio receiver can only operate when the received signal energy is greater than its sensitivity threshold. We define γ^{thr} as a transmission threshold which determines the condition for performing the transmissions. Data transmission is performed only if the received signal energy at the receiver reaches this threshold level. In order to determine the minimum condition in which the URC becomes feasible, we presume that the transmitter sends information with the maximum allowed power. Let's assume that the probability of instantaneous signal strength at the receiver over the fading channel has distribution function $f(\gamma)$. Reliable communications is feasible only if the received signal outage probability is less than the acceptable failure rate target for the communications ($\int_0^{\gamma^{thr}} f(\gamma) d\gamma < \epsilon$). The signal outage results in transmission disruption which degrades the reliability of the communications. In order to meet the desired reliability and compensate the transmission disruption, data transmissions should be performed with a higher level of reliability when the signal is not in the outage states. A tighter BLER value for data transmission can be defined as:

$$\epsilon' = \frac{\epsilon - \Pr(\gamma < \gamma^{thr})}{1 - \Pr(\gamma < \gamma^{thr})}. \quad (7)$$

Data transmissions with a BLER value not exceeding ϵ' ensures that the communication failure (due to transmission disruption and error in decoding the transmitted message) rate is less than ϵ . The average of required radio resources for URC operation over the considered wireless link can be calculated

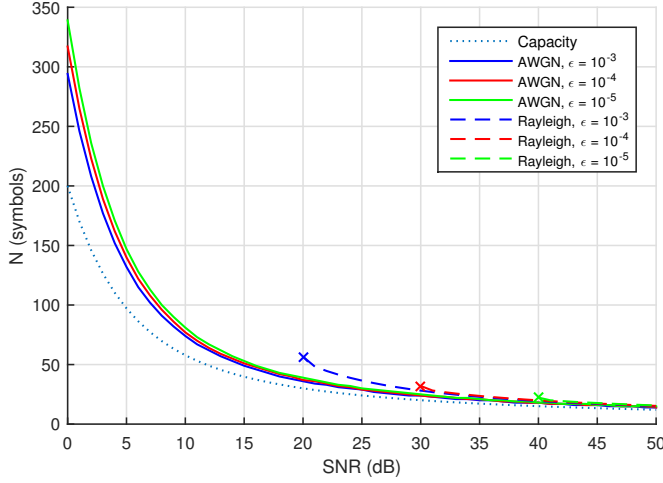


Fig. 1. Minimum number of symbols for transmitting 100 bits over an AWGN and a Rayleigh channels.

as:

$$N(k, \epsilon', f(\gamma)) = \int_{\gamma^{thr}}^{\infty} N_{AWGN}(k, \epsilon', \gamma) f(\gamma) d\gamma. \quad (8)$$

Note that these results are based on the assumption that there is no limit on the level of modulation and the complete CSI is provided at the transmitter. Fig. 1 illustrates the required symbols for transmitting $k = 100$ bits of data over an AWGN channel with three different failure rate targets. In addition, the required symbols according to the Shannon capacity formula are shown as a reference. The considered amount of data is a typical value for many time-critical systems, such as industrial automation applications [11]. This figure also depicts the average of symbols required to achieve these reliability targets over an Rayleigh fading channel. For the fading channel, the transmission threshold is set to $\gamma^{thr} = -10$ dB and a single-antenna system is assumed for both the transmitter and the receiver. Hence, the received signal at the receiver follows an Exponential distribution [12]. It can be observed that the high reliability constraints for URC require additional resources compared to the Shannon capacity which is achievable for long code lengths. A higher level of reliability or lower SNR level increase the number of required resource. It is evident that a certain level of reliability over the Rayleigh fading channel is feasible when the average SNR is higher than a level. This level depends on the accepted failure rate for the communications. For instance, the reliability targets of 99.9%, 99.99%, and 99.999% are achievable for the average SNR values greater than 20, 30, and 40 dB, respectively. This is due to the fact that for lower SNR levels the signal outage probability becomes greater than the accepted failure target.

B. Spatial diversity with no retransmission

It was noted that the channel quality plays an important role in the provision of URC. The link quality can be improved by gaining from spatial diversity, deployment of multiple-antennas at the transmitter or the receiver sides. The combined

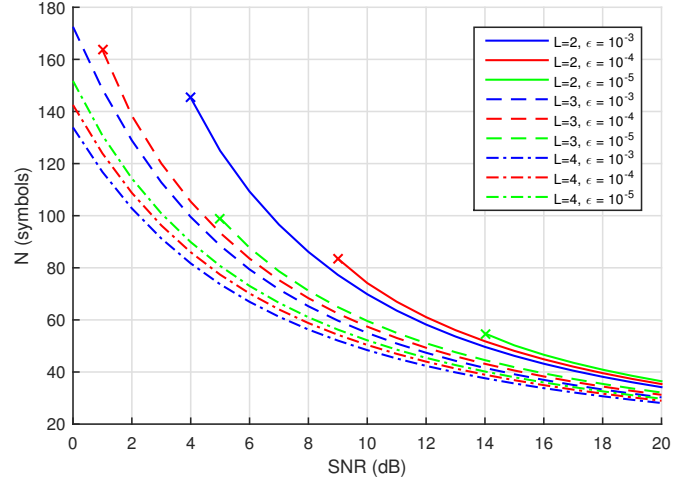


Fig. 2. Minimum number of symbols for transmitting 100 bits over a Rayleigh channel with different spatial diversity orders.

signal from different paths is more robust against the fading [13]. For instance, massive MIMO system is considered as a practical solution for gaining spatial diversity by increasing the number of antennas at a base station dramatically [5]. For the transmit diversity, CSI should be provided for the transmitter which results in higher signaling overhead in the feedback channel. In contrast, the receive diversity needs to perform channel estimation for all individual channel realizations to combine signals from different paths coherently.

Let's assume that the received signal at the receiver over the fading channel has the distribution function $f(\gamma)$ when the spatial diversity is exploited (using multi-antennas at the transmitter or receiver, or at the both sides). A certain level of reliability is achievable only if the signal outage probability is less than the accepted failure rate. If this condition is hold, a tighter BLER value should be set for the data transmissions leading to equation (7). The average number of required resources can also be calculated according to equation (8).

Fig. 2 illustrates the average required symbols to transmit data in the mentioned scenario with different diversity orders. It can be observed that URC operation is feasible at much lower SNR levels when spatial diversity is exploited compared to the case of utilizing SISO antenna system (compared with Fig. 1). A higher diversity order also reduces the required resources for a given level of reliability.

C. Spatial diversity with HARQ

The high reliability and low-latency constraints in the communications entail to use more resources for data transmissions. HARQ is an effective scheme enables improving the radio resources utilization. It allows to transmit data incrementally if decoding the data is unsuccessful [14]. HARQ is formed by using the conventional automatic repeat request scheme along with forward-error correction methods. In this method, a message is encoded and segmented into different parts. A transmitter sends the first part of the data, while a receiver tries to decode the message. If the receiver decodes

the message successfully, it sends an acknowledgement (ACK) message and informs the transmitter to not transmit other parts. In case the receiver cannot retrieve the message without error, it sends a negative acknowledgment (NACK) message to the transmitter and requests for data retransmissions. The data retransmissions are continued until the receiver decodes the message successfully, or the maximum number of retransmissions are reached.

To implement HARQ scheme in URC with low-latency, it is recommended to support only one retransmission [4]. Hence, here we assume that the transmitter has the possibility of maximum two times of data transmissions for sending each payload. As we expect that the shorter TTI gets implemented for URC, we consider the case where the channel condition does not vary from the first transmission attempt to the second one. The main purpose of HARQ scheme is to minimize the utilized radio resources while meeting the required reliability. Let's start with an AWGN channel case and presume that the signal strength at the receiver is γ . We define n_1 and n_2 as the number of symbols which the transmitter intends to utilize in the initial transmission and the retransmission attempt (if it is required), respectively. The BLER for this condition can be expressed as:

$$E_{AWGN}(n_1, n_2, k, \gamma) = 1 - \{(1 - E_{AWGN}(n_1, k, \gamma)) + E_{AWGN}(n_1, k, \gamma)(1 - \xi_{NACK}) (1 - \frac{E_{AWGN}(n_1 + n_2, k, \gamma)}{E_{AWGN}(n_1, k, \gamma)})\}, \quad (9)$$

where ξ_{NACK} indicates the error probability in decoding NACK messages over the feedback channel, which results in not performing the essential retransmission. This equation shows that the message is delivered successfully if the receiver can decode the message without error either using the first data part, or using both data parts when the NACK message is decoded successfully. The probability of decoding the message successfully using two data parts is calculated according to the conditional probability, knowing that decoding the first part was unsuccessful. The expected number of utilized symbols in this case can be expressed as:

$$\mathbb{E}[N_{AWGN}(n_1, n_2, k, \gamma)] = n_1 \{(1 - E(n_1, k, \gamma))(1 - \xi_{ACK}) + E(n_1, k, \gamma)\xi_{NACK}\} + (n_1 + n_2) \{E(n_1, k, \gamma)(1 - \xi_{NACK}) + (1 - E(n_1, k, \gamma))\xi_{ACK}\}, \quad (10)$$

where ξ_{ACK} represents the error probability in decoding the ACK messages. This error results in performing unnecessary retransmissions and does not affect the reliability of data transmissions. The minimum number of utilized symbols can be derived by choosing n_1 and n_2 in order to minimize (10)

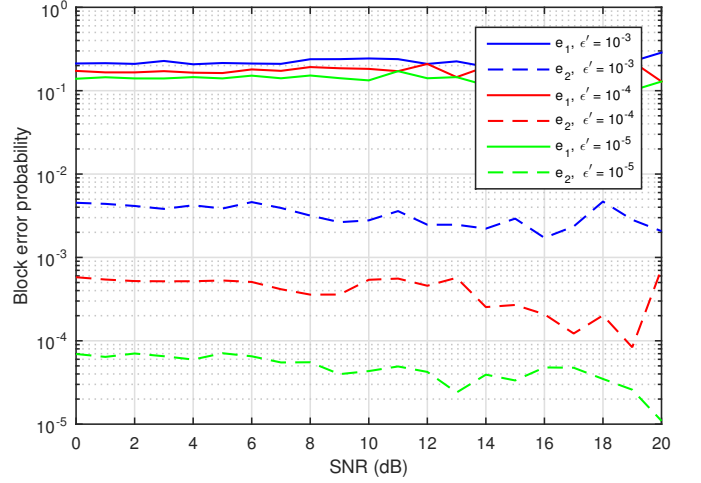


Fig. 3. Efficient block error probabilities for the first transmissions and re-transmissions for different reliability targets. $e(n1) = E(n1, k, \gamma)$, $e(n2) = E(n1 + n2, k, \gamma)/E(n1, k, \gamma)$.

and satisfy the required reliability:

$$N_{AWGN}(k, \epsilon, \gamma) = \min_{n_1, n_2 \in \mathbb{Z}} \mathbb{E}[N_{AWGN}(n_1, n_2, k, \gamma)] : E_{AWGN}(n_1, n_2, k, \gamma) \leq \epsilon \quad (11)$$

Fig. 3 demonstrates the efficient block error probabilities for the first data transmissions and the retransmissions for three different reliability targets. It is evident that HARQ scheme allows performing the first data transmissions with moderate BLER values. For all the considered reliability targets, the first data transmissions can be performed with BLER values around 10%. However, the retransmission attempts should be performed with a higher success rate which depends on the desired reliability level.

Now, we consider a fading channel. Assuming that the received signal at the receiver has distribution function $f(\gamma)$, URC is feasible if the signal outage probability is less than the failure target. A tighter BLER value should be selected for data transmissions according to (7). Finally, the average required symbols for data transmissions over the fading channel can be represented as:

$$N(k, \epsilon', f(\gamma)) = \int_{\gamma_{thr}}^{\infty} N_{AWGN}(k, \epsilon', \gamma) f(\gamma) d\gamma. \quad (12)$$

Fig. 4 illustrates the average required symbols for data transmission over a Rayleigh channel employing HARQ scheme and allowing one retransmission attempt. It is assumed that there is no error in decoding the ACK/NACK messages ($\xi_{ACK} = 0, \xi_{NACK} = 0$). Although using HARQ scheme does not change the SNR levels in which URC becomes achievable, it improves the radio resource utilization (compared Fig. 2). In addition, when the URC is achievable for a high level of reliability, only slightly more radio resources are required compared to a lower level of reliability.

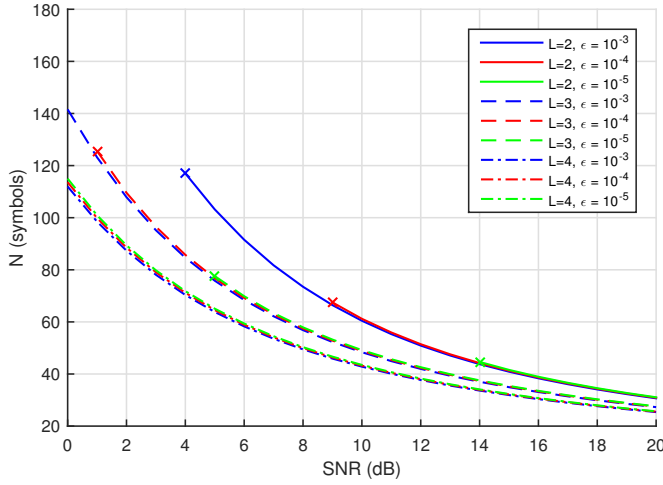


Fig. 4. Minimum number of symbols for transmitting 100 bits over a Rayleigh channel using HARQ with different spatial diversity orders.

IV. CHANNEL FEEDBACK ERROR

In the previous section, we assessed the viability of URC operation in wireless systems. We assumed that the feedback channel operates flawlessly by providing accurate CSI and delivering ACK/NACK messages without error. This section analyzes the impact of errors in decoding ACK/NACK messages where the HARQ scheme is employed. The errors in decoding ACK/NACK messages degrades the performance and reliability of communications. The error may happen due to noise or interference in the system. Equations (9) and (10) represent the impact of these errors on the reliability and the resource utilization. The error in decoding ACK messages does not affect the reliability and merely results in unnecessary data transmissions. On the other hand, the error in decoding NACK messages primarily results in reducing the reliability. In order to compensate this effect, more radio resources should be utilized.

Fig. 5 illustrates the optimum block error probabilities for the first transmissions and retransmission attempts with error in decoding NACK messages. This indicates that HARQ scheme is not sensitive to very small values of error in NACK messages comparing to the transmission failure rate. However, when the error rate in decoding NACK messages becomes comparable to the accepted failure rate for the transmissions, the first data transmissions should be performed more reliable, while the reliability in the retransmissions is decreased. This degrade the resource utilization efficiency as more resources should be allocated for the first data transmissions. The effect of excess in the required resources for the first data transmissions is more than the reduction in the required resource for the retransmissions. This is as a result that the majority of messages should be successfully delivered with the first transmission attempts.

V. CONCLUSIONS

In this paper, we have investigated the feasibility of URC over wireless links. The analysis show the challenge of provid-

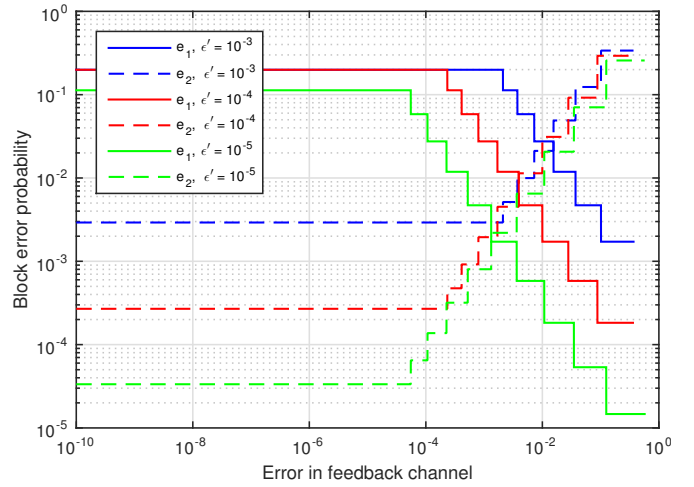


Fig. 5. Efficient block error probabilities for the first transmission and retransmission with feedback error for different reliability targets, at $\gamma = 15$ dB.

ing reliable communications in terms of link quality and radio resource utilization. It is found that spatial diversity improves the link quality significantly, while HARQ scheme boosts the efficiency of radio resource utilization. However, the efficiency improvement obtained by HARQ scheme depends on the accuracy of feedback channel. The uncertainty in feedback channel reduces the gain.

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